

Origin of matter in the universe

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We extend the standard model with two iso-singlet color triplet scalars, one singlet real scalar and one singlet fermion. The new fields are odd under an unbroken Z_2 discrete symmetry while the standard model particles are even. The decays of the singlet real scalar into three standard model quarks (antiquarks) with three singlet antifermions (fermions), which explicitly violate the baryon number, will become effective after the electroweak phase transition and then produce the observed baryon asymmetry in the universe through the loop diagram involving the exchange of the W gauge boson. The singlet fermion can serve as the candidate for cold dark matter. In our model, all new particles with masses below the TeV scale can be detected by the forthcoming collider experiments or the next generation experiments for neutron-antineutron oscillations.

Introduction: Nowadays the baryon asymmetry in the universe has been confirmed by the precise data from the cosmological observations [1]. This puzzle can be elegantly solved by the leptogenesis mechanism [2] proposed by Fukugita and Yanagida about twenty years ago. The salient feature of leptogenesis is that the sphaleron processes [3] partially convert the produced lepton asymmetry to the final baryon asymmetry before the electroweak phase transition. However, the cosmological observations [1] only indicate that the present baryon asymmetry should arise before the big bang nucleosynthesis (BBN). In other words, any theory can solve this puzzle as long as it produces an adequate baryon asymmetry before the BBN even if it becomes effective after the electroweak phase transition. Recently, Babu, Mohapatra and Nasri proposed an interesting mechanism named as post-sphaleron baryogenesis [4, 5], which need not resort to the sphaleron processes, to explain the baryon asymmetry in the universe.

Another major cosmological puzzle is the dark matter, which contributes about 20% to the energy density of our universe [1]. What is the nature of dark matter? One of the popular candidates for dark matter is the weakly interacting massive particles (WIMPs). Among many possible WIMPs, the lightest superparticle (LSP) in supersymmetric models is the most widely studied one. However, no direct experimental evidence has been obtained for supersymmetry so that other possibilities of WIMPs, which explain the relic density of dark matter in the universe, should be worth studying and searching for.

In this paper, we present a nonsupersymmetric model to simultaneously solve the puzzles of baryon asymmetry and dark matter in the universe by extending the standard model (SM) with some new fields. The baryon asymmetry can be produced after the electroweak phase transition through the loop diagram involving the exchange of the W gauge boson. The relic density of cold dark matter can be also realized as desired. In our model, all new particles with masses below the TeV scale can be tested by the forthcoming or proposed experiments.

The model: We extend the $SU(3)_c \times SU(2)_L \times U(1)_Y$ SM with one singlet real scalar A , two iso-singlet color triplet scalars B, C with hypercharge $+\frac{2}{3}, -\frac{1}{3}$, respectively and one singlet fermion S . We further introduce an unbroken Z_2 discrete symmetry, under which the new fields carry odd parity while the standard model particles are all even. Obviously, the present model is free of gauge anomaly. Within this framework, we have the unique baryon number violated interaction,

$$-\mathcal{L} \supset \lambda A B C^2 + \text{h.c.} \quad (1)$$

Furthermore, the new fields can communicate with the SM particles through the following Yukawa couplings,

$$-\mathcal{L} \supset f_i B \overline{u_{Ri}} S + h_i C \overline{d_{Ri}} S + \text{h.c.}, \quad (2)$$

where $u_{Ri}(\mathbf{3}, \mathbf{1}, +\frac{2}{3})$ with $i = (u, c, t)$ is the SM up-type right-handed quark while $d_{Ri}(\mathbf{3}, \mathbf{1}, -\frac{1}{3})$ with $i = (d, s, b)$ is the down-type. As for the other couplings of the new scalar fields to the SM Higgs boson $\phi(\mathbf{1}, \mathbf{2}, -\frac{1}{2})$, they can be made negligible by choice of parameters which do not affect our discussions.

Before discussing how to realize the generation of baryon asymmetry and the relic density of dark matter, let us first clarify why the dangerous proton decay, which appears in the usual models with the color triplet fields [4], can be avoided in our model. Benefited from the exact Z_2 , the singlet real scalar will not develop its vacuum expectation value, the following Yukawa interactions,

$$-\mathcal{L} \supset g_{i\alpha} C \overline{u_{Ri}} l_{R\alpha}^c + y_\alpha \overline{\psi_{L\alpha}} \phi S + \text{h.c.}, \quad (3)$$

will also be forbidden. Here $\psi_{L\alpha}(\mathbf{1}, \mathbf{2}, -\frac{1}{2})$ and $l_{R\alpha}(\mathbf{1}, \mathbf{1}, -1)$ with $\alpha = (e, \mu, \tau)$ are the SM left-handed and right-handed leptons, respectively. Therefore, it is impossible to realize the proton decay as shown in Fig. 1, in which the proton will either decay into one charged lepton and two singlet fermions through a dimension-9 operator suppressed by

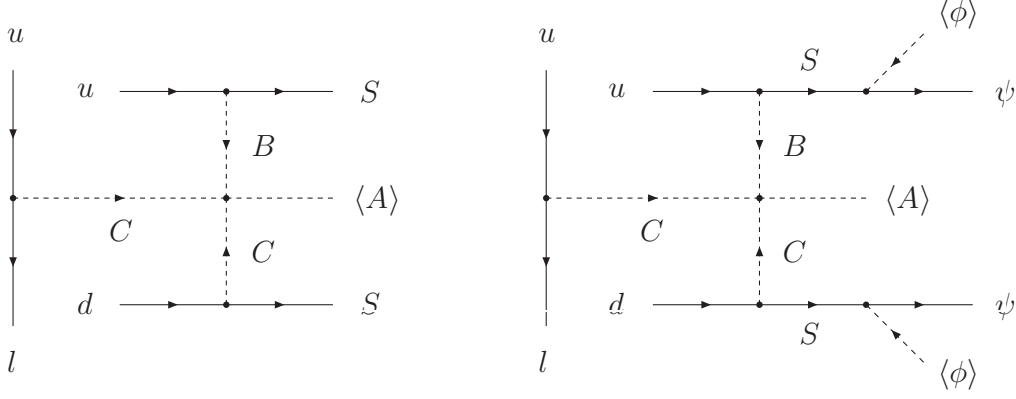


FIG. 1: The proton decay in the case without the present Z_2 . The left diagram shows the proton decay mode with the light singlet Dirac fermion while the right is with the heavy one. Here the diagrams with the singlet fermion being a Majorana particle have been omitted for simplicity.

$\frac{\langle A \rangle}{M_B^2 M_C^4}$ if the singlet fermion is light, or decay into one charged lepton and two neutrinos through another dimension-9 operator suppressed by $\frac{\langle \phi \rangle^2 \langle A \rangle}{M_S^2 M_B^2 M_C^4}$ if the singlet fermion is heavy.

Baryon asymmetry: We begin to demonstrate how to generate the observed baryon asymmetry in the universe after the electroweak phase transition in our model. For this purpose, we assume the following hierarchical mass spectrum for the new fields,

$$M_S \sim 150 \text{ GeV}, \quad M_A \sim 500 \text{ GeV}, \quad M_{B,C} \sim 600 \text{ GeV}. \quad (4)$$

Therefore, the singlet real scalar A can interact with three SM (anti)quarks with the baryon number violation, $\Delta B = (-)1$, by the exchange of the iso-singlet color triplet scalars B, C . For example, Fig. 2 gives the tree level process of the singlet real scalar decaying into three quarks and three singlet antifermions. Following [4], we can see any pre-existing baryon asymmetry will be erased here since there are baryon number violated interactions, which remain in equilibrium at least down to T_* determined by

$$\frac{1}{(2\pi)^9} |\lambda \tilde{f} \tilde{h}|^2 \frac{T_*^{13}}{M_{B,C}^{12}} \leq \frac{g_*^{\frac{1}{2}} T_*^2}{M_{\text{Pl}}} \quad (5)$$

with \tilde{f} and \tilde{h} being the largest of f_i and h_i . The left-handed side of the above equation is, indeed, the temperature-dependent decay rate of the singlet real scalar. It is straightforward to see $T_* \simeq 0.2 M_{B,C}$ with the mass spectrum (4) and $\lambda \sim 0.2$, $\tilde{f} \sim \tilde{h} = \mathcal{O}(1)$ by inputting the Planck mass $M_{\text{Pl}} \simeq 1.2 \times 10^{19} \text{ GeV}$ as well as the relativistic degrees of freedom $g_* = \mathcal{O}(100)$ for the temperature above a few GeV.

However, as a consequence of the expansion of the universe, the decay rate of the singlet real scalar will become a constant as soon as the temperature falls below its mass,

$$\Gamma_A \simeq \frac{N_c P}{6^{12} \times (2\pi)^9} |\lambda|^2 \text{Tr}(f^\dagger f) [\text{Tr}(h^\dagger h)]^2 \frac{M_A^{13}}{M_{B,C}^{12}}, \quad (6)$$

where $f \equiv (f_u, f_c)^T$, $h \equiv (h_d, h_s, h_b)^T$, $N_c = 9$ is a color factor and $P \simeq 2.05$ [4], computed via Monte Carlo methods, is the phase space factor of the six body decay. Here the top quark is absent in the decay products due to the choice of the mass spectrum (4). By equating the above decay rate to the expansion rate of the universe,

$$H \simeq 1.66 g_*^{\frac{1}{2}} \frac{T^2}{M_{\text{Pl}}}, \quad (7)$$

we obtain

$$T_d \simeq \left[\frac{N_c P |\lambda|^2 \text{Tr}(f^\dagger f) [\text{Tr}(h^\dagger h)]^2 M_{\text{Pl}} M_A^{13}}{1.66 g_*^{\frac{1}{2}} (2\pi)^9 (6 M_{B,C})^{12}} \right]^{\frac{1}{2}}, \quad (8)$$

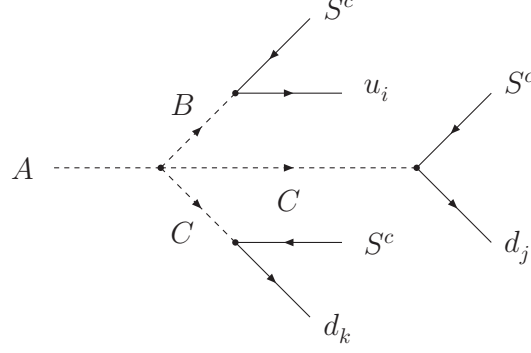


FIG. 2: The singlet real scalar field decays into three SM quarks and three singlet antifermions at tree level.

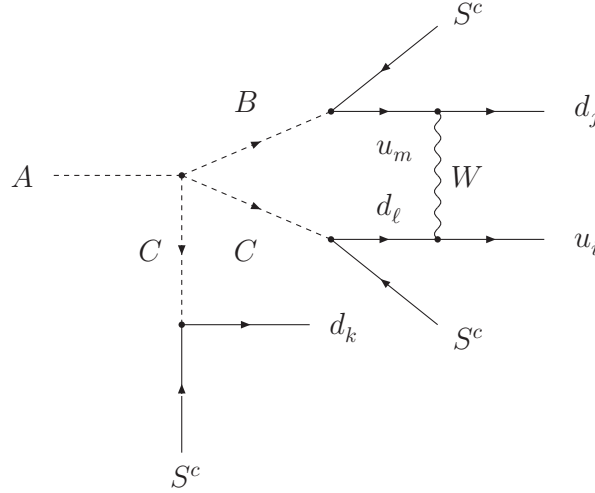


FIG. 3: The singlet real scalar field decays into three SM quarks and three singlet antifermions through the loop diagram involving the exchange of the W gauge boson.

at which A will start to decay. For instance, we deduce,

$$T_d \sim 16 \text{ GeV} \quad (9)$$

with the mass spectrum (4) as well as $\lambda \sim 0.2$, $\text{Tr}(f^\dagger f) \sim \text{Tr}(h^\dagger h) = \mathcal{O}(10)$. This is consistent with our purpose that the decay of the singlet real scalar becomes effective before the BBN.

We now proceed to calculate the CP asymmetry which is necessary for the dynamical generation of baryon asymmetry. Being a real scalar field, A can decay into not only three quarks with three singlet antifermions, $A \rightarrow u_i d_j d_k S^c S^c S^c$ but also three antiquarks with three singlet fermions, $A \rightarrow u_i^c d_j^c d_k^c S S S$. The first decay channel at tree level has been shown in Fig. 2. If the CP is not conserved, the branch ratios of the two decay channels should be different and hence the baryon asymmetry could be expected. To generate the CP asymmetry, we need the loop corrections to interfere with the tree level diagram. It is definitely possible to realize this goal by introducing other singlet real scalars. However, we shall not adopt this approach since within the current framework an effective loop diagram has

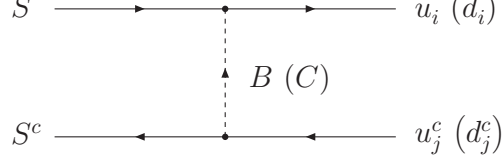


FIG. 4: The singlet fermion-antifermion pair annihilates into the SM quarks through the exchange of the iso-singlet color triplet scalars.

been existing with the exchange of the W gauge boson as shown in Fig. 3. We derive the CP asymmetry,

$$\varepsilon \simeq \frac{G_F}{\sqrt{2}\pi} \frac{\text{Im} \left[\text{Tr} \left(V^T \hat{M}_u f f^\dagger V^* \hat{M}_d h h^\dagger \right) \right]}{\text{Tr} (f^\dagger f) \text{Tr} (h^\dagger h)}, \quad (10)$$

where G_F is the Fermi constant, V is the CKM matrix, $\hat{M}_u = \text{diag} (m_u, m_c, m_t)$ and $\hat{M}_d = \text{diag} (m_d, m_s, m_b)$. Note with the present choice of the mass spectrum (4), the contribution from the top quark should be absent in Eq. (10). We thus have

$$\varepsilon \sim 10^{-7} \sin \delta \quad (11)$$

for $G_F = 1.17 \times 10^{-5} \text{ GeV}^{-2}$, $V_{cb} = 0.04$, $m_b = 4.20 \text{ GeV}$, $m_c = 1.25 \text{ GeV}$, $f_c f_b^* \sim h_b h_c^* = \mathcal{O}(1 - 10)$ and $\text{Tr} (f^\dagger f) \sim \text{Tr} (h^\dagger h) = \mathcal{O}(10)$ with δ being the CP phase.

The final baryon asymmetry can be expressed as

$$\eta_b \equiv \frac{n_b}{s} = \left(\frac{n_b}{n_A} \right) \left(\frac{n_A}{s} \right) \simeq \varepsilon \frac{T_d}{M_A}, \quad (12)$$

where $s = (2\pi^2/45) g_* T_d^3$ is the entropy density and n_A/s denotes the dilution from reheating. By using Eqs. (8) and (11), we eventually obtain

$$\eta_b \simeq 10^{-10} \quad (13)$$

for the appropriate CP phase, and hence successfully explain the observed baryon asymmetry in the universe [1].

Dark matter: We now discuss the possibility of the singlet fermion as the cold dark matter. Since the singlet fermion is forbidden by the exact Z_2 symmetry to have the Yukawa couplings with the SM lepton and Higgs iso-doublets, it can not decay into any SM particles, and become an attractive candidate for dark matter. As shown in Fig. 4, the singlet fermion-antifermion pair can annihilate into the SM quarks through the exchange of the iso-singlet color triplet scalars. We have

$$\langle \sigma v \rangle \simeq \frac{[\text{Tr} (f^\dagger f)]^2 + [\text{Tr} (h^\dagger h)]^2}{4\pi} \frac{M_S^2}{M_{B,C}^4}, \quad (14)$$

where σ is the total annihilation cross section of a singlet fermion-antifermion pair, v is the relative speed between S and S^c in their center-of-mass system (cms), $\langle \dots \rangle$ denotes the thermal average. Here we have used the good approximation that for cold dark matter the average cms energy is roughly equal to $4M_S^2$. For the mass spectrum (4) with $\text{Tr} (f^\dagger f) \sim \text{Tr} (h^\dagger h) = \mathcal{O}(10)$, the cross section (14) is about equal to 1 pb as would be desired to generate the right amount [1] of the relic density for cold dark matter.

Collider signals: We shall expect the iso-singlet color triplet scalars as well as the singlet fermion to be observable in the collider experiments such as the forthcoming LHC since their masses are below the TeV scale. As shown in Fig. 5, the colored scalars B, C can be produced either singly via the processes, $u_i + d_j^c \rightarrow B + C^*$, $d_i + u_j^c \rightarrow C + B^*$, or in pairs via the processes, $u_i + u_j^c, d_i + d_j^c \rightarrow B + B^*, C + C^*$. The two types of colored scalars can be distinguished by their decays into the top or bottom quarks. As for the singlet fermion, it can be produced by the annihilations of the SM quark-antiquark pairs as shown in Fig. 6.

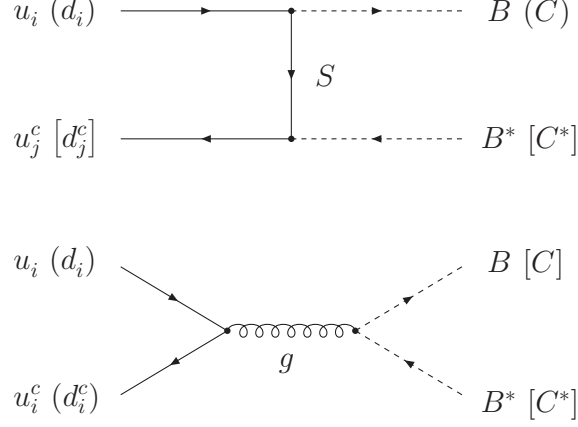


FIG. 5: The SM quark-antiquark pairs annihilate into the iso-singlet color triplet scalars through the exchange of the singlet fermion or the gluons. Here g denotes the gluons.

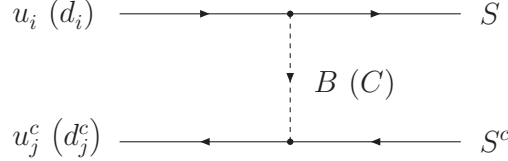


FIG. 6: The SM quark-antiquark pairs annihilate into the singlet fermions through the exchange of the iso-singlet color triplet scalars.

Neutron-antineutron oscillations: Our model can predict a neutron-antineutron oscillation through a three loop diagram as shown in Fig. 7, if the singlet fermion is a Majorana particle. The effective strength of this neutron-antineutron oscillation should be

$$G_{N-\bar{N}} \simeq \frac{3(\lambda^*)^2 f_u^2 h_d^4}{(2\pi)^{12}} \frac{M_S^9}{M_A^2 M_{B,C}^{12}} \quad (15)$$

by taking the cutoff at M_S . For the mass spectrum (4) with $\lambda \sim 0.2$, $f_u^2 \sim h_d^2 = \mathcal{O}(1-10)$, we have $G_{N-\bar{N}} \sim (10^{-30} - 10^{-27}) \text{ GeV}^{-5}$ to be consistent with its upper bound, $G_{N-\bar{N}} \leq 10^{-27} \text{ GeV}^{-5}$, which corresponds to the present limit on $\tau_{N-\bar{N}} \sim 10^8 \text{ sec}$ [6].

Note that the present limit on the neutron-antineutron oscillations can be improved by two orders of magnitude

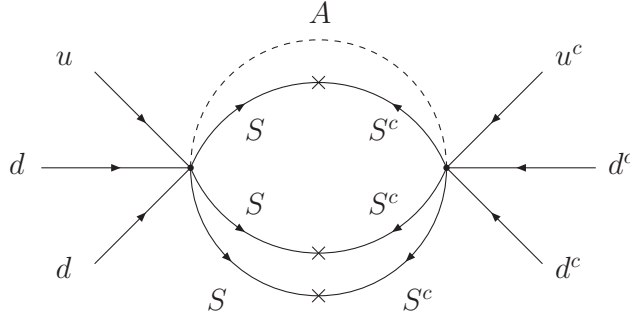


FIG. 7: The neutron-antineutron oscillation is generated by the three loop diagram if the singlet fermion is a Majorana particle. Here the internal iso-singlet color triplet scalars have been integrated out for simplicity.

in the future [7]. It is therefore attractive that the neutron-antineutron oscillations can be in the range accessible to experiments and hence can be used to test our model. We should point out that in contrast to the confirmed prediction of Refs. [4, 5], the neutron-antineutron oscillations of our model would be absent if the singlet fermion is of Dirac nature. Meanwhile, even if the neutron-antineutron oscillations were ruled out in the future, our model would be still valid for solving the puzzles of baryon asymmetry and dark matter since the singlet fermion is free to be a Majorana or Dirac particle in the current framework.

Conclusion: In this paper, we extend the SM with two iso-singlet color triplet scalars, one singlet real scalar and one singlet fermion. The decays of the singlet real scalar into three quarks (antiquarks) with three singlet antifermions (fermions) through the loop diagram involving the exchange of the W gauge boson will become effective after the electroweak phase transition and then producing the observed baryon asymmetry in the universe. The singlet fermion-antifermion pair can annihilate into the SM quarks and thus obtain a desired relic density to explain the puzzle of dark matter. The neutron-antineutron oscillations will be possible to occur in the case where the singlet fermion is a Majorana particle. Our model can be testable at the forthcoming experiments collider experiments or the next generation experiments for neutron-antineutron oscillations.

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